The Dynamics of Tropical Cyclones

Roger K. Smith
Meteorological Institute
University of Munich
Theresienstr. 37, 80333 Munich, Germany
phone +49 (89) 2394-4383 fax +49 (89) 2394-4182 email roger@meteo.physik.uni-muenchen.de
Award #: N000149510394
http://www.meteo.physik.uni-muenchen.de

LONG-TERM GOALS

The broad objectives of this research effort are to improve our understanding of the dynamics of tropical-cyclone evolution and motion using a combination of analytic techniques, observational case studies and numerical model calculations, and to apply this knowledge to improve numerical tropical-cyclone forecasts.

OBJECTIVES

The specific objectives of the current effort are:

1. To continue our study of the dynamical processes in tropical cyclones responsible for looping or erratic motion;
2. To continue the development of methods for (a) the introduction of synthetic tropical-cyclone-scale vortices in operational forecast models and (b) ensemble forecasting of tropical cyclones;
3. To continue a sensitivity study of track forecasts with a simple numerical model, focusing on different initialization strategies and using initial data sets from different forecast centres;
4. To continue our study of the dynamics of the extra-tropical transition of tropical cyclones with emphasis on idealized modelling;
5. To continue our study of tropical cyclone intensity change processes and motion in three dimensions via potential vorticity anomalies or vortex Rossby waves;
6. To elucidate the physical mechanisms underlying changes in hurricane structure and intensity, including rapid deepening and eyewall replacement cycles;
7. To diagnose hurricane track and intensity change as predicted by the Geophysical Fluid Dynamics Laboratory (GFDL) hurricane model using the technique of potential vorticity inversion;
8. To continue a numerical modelling study of tropical-cyclone - trough interaction;
9. To continue a study of the factors which govern the size of tropical cyclones;
10. To continue a numerical modelling study of midget typhoons; and
11. To initiate a numerical and theoretical study of the spin down of tropical cyclone vortices;
12. To initiate collaboration with the German Weather Service (DWD) to improve the prediction of tropical cyclones with the DWD's global model.

APPROACH

The approach involves a mix of analytical and numerical model calculations, as well as the analysis of operational and field data. Recent findings from theoretical studies are being applied to the problem of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 1999		**00-00-1999 to 00-00-1999**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
The Dynamics of Tropical Cyclones	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Munich,Meteorological Institute,Theresienstr. 37,80333 Munich, Germany,**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

initializing tropical cyclones in numerical forecast models. Group members in addition to the PI include: Drs. Sarah Jones (working on the effects of vertical shear on vortex evolution and on the extra-tropical transition of tropical cyclones), Dominique Möller, (working on the influence of potential vorticity anomalies on tropical cyclone intensity change and on diagnosing hurricane track and intensity change as predicted by the GFDL hurricane model), Maria Peristeri (working on a a modelling study of midget typhoons), Lloyd Shapiro (working on potential vorticity asymmetries and tropical cyclone evolution), Wolfgang Ulrich (working with doctoral student, Ms. Hongyan Zhu, on the development of an idealized hurricane model), and Harry Weber (working on aspects of tropical cyclone dynamics relevant for tropical-cyclone motion and the forecast of tropical-cyclone motion, and with doctoral student Markus Adams on the development of a barotropic forecast model for hurricane prediction).

WORK COMPLETED

We have completed a revised version of a paper on the dynamics of vortices in vertical shear and this has been submitted for publication (Smith et al., 1999).

We have developed a new three-level, three-dimensional hurricane model with an option to include three different representations of cumulus convection. Realistic simulations of hurricanes have been carried out with the model. The model will be used for basic studies of tropical cyclone evolution in a variety of environments including cyclone behaviour in the presence of an approaching upper-level trough. An axisymmetric version of the model has been developed and will be used for our study of the factors governing the size of tropical cyclones.

We have completed a study of the convective destabilization by an approaching upper level trough and a joint paper on this topic with a colleague, Dr. Martin Juckes, has been accepted for publication (Smith and Juckes, 2000).

We organized a workshop on 'The extratropical transition of tropical cyclones' which was held in Kaufbeuren, Germany from 10-14 May 1999 and was sponsored by ONR and the WMO Tropical Meteorology Research Programme. The workshop brought together forecasters and researchers from most of the countries affected by extratropical transition, notably from the United States, Canada, Australia and countries in western and central Europe. During the workshop presentations were made which described the problems associated with forecasting extratropical transition, the current state of knowledge of extratropical transition and relevant theoretical ideas. Working groups were formed to discuss the issues raised in the presentations and to formulate recommendations aimed at improving the understanding and forecasting of extratropical transition. The abstracts of the presentations and the recommendations of the workshop will be published as a WMO report. A summary of the workshop is in preparation also and will be submitted to the *Bulletin of the American Meteorological Society*.

We have completed a first study of the effect of potential vorticity asymmetries and tropical cyclone evolution in a moist three-layer model. A paper describing the results of the research has been submitted for publication (Shapiro, 1999).

We have completed a case study of hurricanes *Felix* and *Iris* (1995) and a paper describing the study has been accepted for publication (Thorncroft and Jones, 2000).

We have prepared a review paper on the role of cumulus convection in hurricanes and its representation in hurricane models (Smith, 1999a,b). The paper includes a framework in which a number of existing schemes can be interpreted and compared. Lectures on this work have been given by the PI at James

Cook University in Townsville, the Australian Bureau of Meteorology Regional Forecast Offices in Darwin and Brisbane, and at the Kaufbeuren Workshop.

A paper describing the results of the study of potential vorticity asymmetries and tropical cyclone motion has appeared in print (Shapiro and Franklin, 1999). Lloyd Shapiro gave an invited presentation on this topic at the Kaufbeuren Workshop (Shapiro and Möller, 1999), and at the Naval Pacific Meteorology and Oceanography Center at Pearl Harbor as well as the Department of Meteorology at the University of Hawaii in June 1999.

Our studies of vortex motion in an asymmetric balance shallow water model and of tropical cyclone evolution via potential vorticity anomalies in a barotropic model have appeared in print (Montgomery, Möller and Nicklas, 1999; Möller and Montgomery, 1999a). A paper extending this work to three dimensions has been submitted for publication (Möller and Montgomery, 1999b). Dominique Möller gave an invited paper on this topic and a summary of her work at the Naval Pacific Meteorology and Oceanography Center at Pearl Harbor as well as at the Department of Meteorology at the University of Hawaii in June 1999.

We have completed a study of polygonal eye walls in hurricanes and their effect on storm motion and a paper on this topic has been submitted for publication (Weber, 1999).

We have completed a comprehensive case study of the structure and motion of a monsoon depression and the third paper in a series of papers has been accepted for publication (Weber and Smith, 1999).

We have continued to collaborate with Dr. Noel Davidson of the Bureau of Meteorology Research Centre (BMRC) to improve the Bureau's Tropical Limited-Area Prediction System (TC-LAPS). A paper describing the results obtained with the modified forecast system has been accepted for publication (Davidson and Weber, 1999). The expert system of TC-LAPS is presently being adapted to the DWD's new operational global forecast model with the aim of improving tropical cyclone track and intensity predictions with this model.

We have extended the new doubly-nested shallow water model to include an initialization procedure similar to that used in the standard BMRC Limited Area model (LAPS). Time-dependent boundary conditions are used from the National Centers for Environmental Prediction's global model forecasts. We have also developed a diagnostic scheme that allows the analysis of the evolution of vortex asymmetries during the period of prediction.

We have developed an ensemble forecast system for LAPS and the system is presently being tested.

We have developed a new software package for evaluating the convective available potential energy and convective inhibition from radiosonde or dropwindsonde soundings.

We have completed an investigation of a new method to analyze the asymmetries of a hurricane from dropwindsonde data for which Helga Weindl was awarded her Diplom degree.

We have completed a study of tropical cyclone intensification involving upper-level cyclone-trough interactions based on data sets from the Tropical Cyclone Motion Experiment (TCM90), the European Centre for Medium Range Weather Forecasts, and the Australian Bureau of Meteorology (BoM). Analyses of the tangential wind changes in an Australian monsoon depression of 1994 and Typhoons *Flo* and *Ed* (1990) were related to the azimuthally averaged absolute vorticity-flux, the potential vorticity-flux, the advection of absolute angular momentum, the Eliassen-Palm flux-divergence, and convective-scale asymmetries. This study forms the basis of Reinhard Hell's doctoral thesis.

RESULTS

Our review on the role of cumulus convection in hurricanes and its representation in hurricane models has shown that all hurricane models produce what the authors claim to be a realistic simulation of a hurricane, irrespective of the convection scheme used. We conclude that all that is required for hurricane intensification is the generation of buoyancy in a region surrounding a (weak) pre-existing circulation centre, and located above the frictional boundary layer so as to produce convergence there. We have found a way to relate several different convection schemes which have been proposed for simple models. The results are a step forward in our efforts to identify which aspects of simulated hurricane behaviour are sensitive to the representation of convection and which are not.

The new three-dimensional hurricane model has, itself, produced a realistic mature hurricane, irrespective of the cumulus parameterization scheme chosen and also in a case where there is no parameterized convection and moist processes are included explicitly. In each case, an initially weak vortex undergoes a period of rapid deepening, which occurs earlier in the case with parameterized convection. In the latter cases, the precipitation is mainly associated with the sub-grid-scale convection in the early stages of evolution and is mainly explicit in the later stages**.** These findings corroborate those of Baik et al. (1990), who use an axisymmetric model that included the Betts-Miller cumulus parameterization scheme. The fidelity of the model augurs well for its use in future basic studies of hurricane evolution.

The study of the role of potential vorticity (PV) asymmetries in the evolution of a tropical cyclone confirms the dominance of horizontal eddy fluxes at early times. The physical mechanism responsible for the differences between barotropic studies and those including moist physics as well as for the robustness of the response is established using a budget for the asymmetric vorticity. It is shown that the interactions between the asymmetries and the symmetric hurricane vortex at early times depend on realistic features of the model hurricane, and not on interactions between the asymmetries and the boundary layer that possibly depend on the convective parameterization. In particular, in conjunction with horizontal advection and damping of "wave activity", the reversal of the radial vorticity gradient associated with the local PV maximum inside the radius of maximum wind constrains the asymmetries to reduce the symmetric vorticity near that radius. The location of the PV maximum constrains the response to the extent that moving the PV anomaly radially inward or outward has no qualitative effect on the results. The longer-term evolution of the vortex is more problematic, and may depend on the convective parameterization used.

We have investigated the mechanism of vortex intensification by vortex Rossby waves (Montgomery and Kallenbach 1997) with a variety of experiments in two and three dimensions. Simple relaxation (“axisymmetrization”) experiments with monochromatic azimuthal-wavenumber disturbances show that vortex Rossby waves propagate both radially and vertically. The higher the wavenumber the weaker the vertical propagation of the PV asymmetries and corresponding response of the basic state. Experiments where double-cluster PV anomalies are superimposed complement the cyclogenesis results of Montgomery and Enagonio (1998). When the ongoing process of convection is simulated by adding double-cluster PV anomalies to the PV fields (so-called “pulsing”), the tropical storm intensifies to hurricane strength whose intensity depends on the location and extent of the anomaly. These results help us to better understand structure change and intensification of hurricanes in a baroclinic setting, and confirm that there exists an alternative means of tropical cyclone intensification to the symmetric mode.

In the analytical/numerical study of polygonal eye-walls, we have shown that in the absence of atmospheric diffusion or in cases of weak atmospheric diffusion, which is possibly the case in real tropical cyclones above the boundary layer, persisting polygonal patterns of relative vorticity may develop in the vortex core. The polygonal vorticity patterns are manifestations of secondary vortices to the original symmetric vortex that are advected about the vortex centre by the swirling flow. Both the analytical and numerical solution agree very well with observations of polygonal eye-walls in real tropical cyclones (Lewis and Hawkins, 1982; Muramatsu, 1986) and may provide a fundamental mechanism for the development of polygonal eye-walls. The existence of secondary vortices of azimuthal wavenumber one leads also to erratic or cycloidal motion of the vortex with important implications for tropical cyclone track prediction.

The study of a monsoon depression over northwestern Australia examines various factors responsible for the motion of the monsoon depression including: (a) the influence of large-scale synoptic weather systems, (b) the influence of mesoscale features in the vicinity of the monsoon depression, (c) the effect of the advection of planetary vorticity by the axisymmetric flow, and (d) the effect of the divergent flow. We have shown that the cross-vortex flow associated with divergence is often of the same magnitude as that associated with relative vorticity. This finding suggests that the effect of the divergent flow on vortex motion cannot be neglected in comparison with the effect of the rotational flow, e. g. during the initialization of numerical prediction models. Features similar to the beta-gyres predicted by theoretical studies could be identified at only one out of twelve synoptic times analyzed in the study. This suggests that processes other than the advection of planetary vorticity by the symmetric vortex are more important for the southwestward drift of the monsoon depression.

The method investigated for analyzing vortex asymmetries turned out to be less successful than might have been expected. The reason appears to lie in the ill-conditioned nature of the minimization problem that arises in the solution procedure.

The new regional prediction model TC-LAPS, with an improved initialization procedure in the form of an expert system, has been very successful in the semi-operational tests carried out during the last year and will soon replace the present LAPS model.

Various ensemble techniques (random methods, singular vector methods and breeding methods) have been applied to an older version of the BoM regional model LAPS. Work on the conception and development of an ensemble forecasting system includes thorough tests and intercomparisons of all methods on selected cases of tropical cyclones in the Australian region.

An improvement of track predictions with the new doubly-nested shallow-water has been obtained by using an initialization strategy where the environmental (large-scale) flow, induced at the vortex centre, is fitted to the vector difference of the observed motion and the flow induced by artificial beta-gyres. The application of time-dependent boundary conditions does not significantly improve the mean forecast error of all 1996 Atlantic hurricane cases examined, although in some cases, the individual forecast error at a given prediction time is reduced.

IMPACT/APPLICATIONS

The results of our PV inversion study have the potential to improve forecasts of tropical cyclone motion and to better predict intensity changes by diagnosing the reasons for good and bad forecasts from the GFDL hurricane model. Intensity changes are currently forecast by operational models with little skill.

The results of the study of potential vorticity asymmetries and tropical cyclone evolution have the potential to improve forecasts of rapid deepening and eyewall replacement cycles by establishing the conditions under which such processes are favored.

The knowledge of the impact of near-core dynamical features such as polygonal eye-walls or secondary wind maxima on the storm track have the potential to improve the quality of operational track forecasts in cases where these features are detected in real tropical cyclones. Special warnings regarding possible sudden track changes could be included in official forecasts of storms with dynamical near-core anomalies.

The work on the initialization procedure of the LAPS model has led to a considerable improvement in the prediction of tropical cyclone tracks with this model. Therefore, it is planned to extend the forecast domain of the new model TC-LAPS to regions other than the traditional regions covered by the BoM (e. g. to the northwestern Pacific Ocean). It is also expected that the adaptation of the initialization procedure to the new DWD global model will improve tropical cyclone track and intensity predictions with this model.

Sensitivity studies are being carried out to generate individual deep layer mean fields that depend on the structure of a particular storm as provided by TC-advisories. Furthermore, the impact of data sets from different forecast centres on barotropic tropical cyclone track predictions are being investigated. These studies may allow an assessment of the quality of data sets provided by individual operational forecast centers for regional prediction models.

The analyses of the azimuthally-averaged, absolute vorticity-flux and small-scale (subgrid-scale) asymmetry effect around tropical vortices provide an alternative framework for diagnosing the effect of upper-level troughs on tangential velocity changes of tropical vortices.

The workshop on the extratropical transition of tropical cyclones enabled leading forecasters and researchers in this area to exchange knowledge and ideas. This workshop should impact future research on extratropical transition leading ultimately to improved forecasts.

TRANSITIONS

The new initialization procedure of TC-LAPS will be operational in the near future. Work continues to further improve the performance of the procedure. Furthermore, the method is presently being implemented in the DWD global model.

The software package for evaluating the convective available potential energy and convective inhibition from radiosonde or dropwindsonde soundings will be used by the Australian Bureau of Meteorology.

RELATED PROJECTS

The work on the effect of potential vorticity asymmetries on tropical cyclone evolution and that on diagnosing hurricane track and intensity change as predicted by the GFDL hurricane model is being carried out in collaboration with Dr. M. T. Montgomery at the Colorado State University.

The work on extratropical transition of tropical cyclones is being carried out in collaboration with Dr. C. Thorncroft at the University of Reading, England.

The work on the initialization of synthetic vortices in numerical prediction models is being carried out in close collaboration with scientists of Dr. K. Puri's Group at the Bureau of Meteorology Research

Centre in Melbourne, Australia, especially with Dr. Noel Davidson, who is mainly responsible for the development and maintenance of the Bureau's regional model.

The work on the new initialization procedure of the global DWD model is in collaboration with Dr. D. Majewski of the DWD, who is responsible for the development and maintenance of the DWD's operational models.

The work on the development of axisymmetric version of our new tropical cyclone model is being carried out in collaboration with by Nguyen Chi Mai, a masters student at Monash University in Australia**.**

The doubly-nested shallow water model is being used by Nguyen Thi Minh Phuong at Monash University for experimental track forecasts of tropical cyclones in the Northwest Pacific region.

REFERENCES

Baik, J.-J., M. DeMaria, and S. Raman, 1990: Tropical cyclone simulations with the Betts Convective adjustment scheme. Part I: Model description and control simulation. *Mon. Wea. Rev*., **118**, 513-528.

Lewis, B. M., and H. F. Hawkins, 1982: Polygonal eye walls and rainbands in hurricanes. *Bull. Amer. Met. Soc*., **63**, 1294-1300.

Montgomery, M. T., and J. Enagonio, 1998: Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model. *J. Atmos. Sci*., **55**, 3176-3207.

Montgomery, M. T., and R. J. Kallenbach, 1997: A theory for vortex Rossby-waves and its application to spiral bands and intensity changes in hurricanes. *Quart. J. Roy. Meteor. Soc*., **123**, 435-465.

Muramatsu, T., 1986: The structure of polygonal eye of a typhoon. *J. Met. Soc. Japan,* **64**, 913-921.

PUBLICATIONS

Davidson, N. E., and H. C. Weber, 1999: The BMRC high resolution tropical cyclone prediction system: TC-LAPS. *Mon. Wea. Rev.* In press.

Jones, S. C., 1999a: The evolution of vortices in vertical shear. II: the role of large-scale asymmetries. Revised version submitted to *Quart. J. Roy. Meteor. Soc.*

Jones, S. C., 1999b: The evolution of vortices in vertical shear. III: baroclinic vortices. Revised version submitted to *Quart. J. Roy. Meteor. Soc.*

Juckes, M. and R. K. Smith, 2000: Convective destabilization by upper-level troughs. *Quart. J. Roy. Meteor. Soc.* In Press.

Montgomery, M. T., J. D. Möller, and C. T. Nicklas, 1999: Linear and nonlinear vortex motion in an asymmetric balance shallow water model. *J. Atmos. Sci*., **56**, 749-768.

Möller, J. D., and M. T. Montgomery, 1999a: Vortex Rossby waves and hurricane intensification in a barotropic model. *J. Atmos. Sci.,* **56**, 1674-1687.

Möller, J. D., and M. T. Montgomery, 1999b: Tropical cyclone evolution via potential vorticity anomalies in a three-dimensional balance model. Revised version submitted to *J. Atmos. Sci*.

Shapiro, L. J., 1999: Potential vorticity asymmetries and tropical cyclone evolution in a moist three-layer model. Revised version submitted to *J. Atmos. Sci*.

Shapiro, L. J. and J. L. Franklin, 1999: Potential vorticity asymmetries and tropical cyclone evolution. *Mon. Wea. Rev.*, **127**, 124-131.

Smith, R. K., 1999a: The role of cumulus convection in hurricanes and its representation in hurricane models. Submitted to *Reviews of Geophysics*.

Smith, R. K., W. Ulrich, and G. Sneddon, 1999: The dynamics of hurricane-like vortices in vertical shear flows. Revised version submitted to *Quart. J. Roy. Meteor. Soc.*

Thorncroft, C. D., and S. C. Jones, 2000: On the extratropical transition of hurricanes Felix and Iris in 1995. *Mon. Wea. Rev.*, In press.

Weber H. C., and R. K. Smith, 1999: A monsoon depression over northwestern Australia: Part III Motion. *Aust. Meteor. Mag.*, In press.

Weber, H. C., 1999: Polygonal eye-walls in barotropic, hurricane-like vortices. Submitted to the *Quart. J. Roy. Meteor. Soc.*

Weber, H. C., 1999: Concentric secondary wind maxima in intense barotropic, tropical-cyclone-like vortices. Submitted to the *Quart. J. Roy. Met. Soc.*

CONFERENCE PAPERS

The following 12 papers were presented at the 23rd AMS Conference on Hurricanes and Tropical Meteorology, held in Dallas in January 1999:

Adams, M., *A new nested shallow-water model for tropical-cyclone track prediction*.

Davidson, N., and H. Weber, *The BMRC high resolution tropical cyclone prediction system: TC-LAPS*

Hell, R. M., *The influence of resolved and subgrid-scale asymmetries on intensity changes of tropical cyclones and monsoon depressions*.

Jones, S. C., and C. D. Thorncroft, *Structural changes of tropical cyclones during extra-tropical transition*.

Juckes, M., and R. K. Smith, *Convective destabilization by tropical upper-level troughs.*

Möller J. D., and M. T. Montgomery, *Hurricane evolution via potential vorticity asymmetries in a three-dimensional asymmetric model.*

Shapiro, L. J., *Convective asymmetries and tropical cyclone evolution in a three-layer model*.

Smith, R. K., and H. Weber, *Motion of a monsoon depression over northwestern Australia*.

Thorncroft, C. D. and S. C. Jones, *On the extra-tropical transition of Hurricanes Felix and Iris 1995*.

Ulrich, W., and R. K. Smith, *The dynamics of baroclinic vortices in vertical shear*.

Weber, H., *A numerical study of tropical-cyclone structure: concentric secondary wind maxima.*

Weindl, H., R. K. Smith and M. A. Pedder, *The detection of hurricane asymmetries from simulated airborne dropwindsonde soundings*.

The following 3 papers were presented at the WMO-sponsored Workshop on the Extratropical Transition of Tropical Cyclones held in Kaufbeuren, Germany from 10 to14 May, 1999 and appear as Extended Abstracts in the WMO Tropical Meteorology Research Programme Report.

Smith, R.K., 1999b: *Convection in hurricanes*.

Jones, S.C. and C.D. Thorncroft, 1999: *Extratropical transition of Atlantic hurricanes: systems which influence the European weather*.

Shapiro, L. J. and J. D. Möller, 1999: *Potential vorticity inversion: an overview*.

THESES

Hell, R., 1999: Synoptische, diagnostische und numerische Untersuchungen der Intensitätsänderungen von tropischen Wirbelstürmen und Monsuntiefs. Doctoral Thesis, University of Munich, 172pp.

Weindl, H., 1999: Detection of hurricane asymmetries from simulated dropwindsonde soundings Diplom Thesis, University of Munich, 80pp.